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Issued August 8, 1907.

U. S. DEPARTMENT OF AGRICULTURE,

OFFICE OF PUBLIC ROADS—BULLETIN NO. 31.

LOGAN WALLER PAGE, Director.

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EXAMINATION AND CLASSIFICATION OF ROCKS FOR ROAD BUILDING,

INCLUDING THE PHYSICAL PROPERTIES OF ROCKS WITH REFERENCE TO THEIR MINERAL COMPOSITION AND STRUCTURE.

BY

EDWIN C. E. LORD,

PETROGRAPHER, OFFICE OF PUBLIC ROADS.

WASHINGTON:
GOVERNMENT PRINTING OFFICE.
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EXAMINATION AND CLASSIFICATION OF ROCKS FOR ROAD BUILDING.

INTRODUCTION.

Since the establishment of the road-material laboratory by the Secretary of Agriculture in December, 1900, more than 1,500 rock samples from nearly every State in the Union, as well as from the islands of Cuba, Porto Rico, and Hawaii, have been examined microscopically and tested to determine their adaptability for road construction.

The main object of the present paper is to describe in some detail the more important quantitative methods of rock analysis by means of the microscope in use in the Office of Public Roads, and to propose a classification of road material suited to the requirements of road builders and engineers. The advantages of such a classification are apparent to every one familiar with work of this kind, and in view of the fact that indefinite and often misleading terms, such as porphyry, trap, greenstone, bluestone, etc., are in common use.[a]

When by means of suitable laboratory tests a road material has been found to satisfy certain conditions of climate and traffic, it is obviously of value to determine its mineral composition for future reference and comparison. It is of interest, furthermore, to inquire how far this mineral composition may be of service in determining beforehand the useful qualities of a rock for road making. It is true that some samples having essentially the same mineral composition may vary greatly in their physical properties,[b] yet it will be shown that rocks of the same general type have in common many qualities rendering them especially adaptable to certain kinds of traffic.

An important feature of the classification will be the arrangement of the rocks in groups or families, according to their average mineral composition, and accompanying these standard analyses will be given their corresponding physical properties. In a discussion of these properties from a mineralogical standpoint special attention will be called to the binding power of the rock powders, and an attempt made to demonstrate that rocks in which one or more of the primary constituents have undergone alteration mainly through the action of atmospheric agencies, yield powders with proportionately higher cementing values than those obtained from their unaltered prototypes. The investigations[a] which have been carried on for a number of years in the laboratories of the Office of Public Roads have demonstrated that the binding power of a rock dust is dependent upon the decompositions which take place under the action of water. In order for a rock to have a high cementing value, it must be of such a nature that these decompositions take place more or less readily. The existence of alteration products in the original rock is therefore to some extent a measure of this quality, although it does not always follow that the alteration products are the direct cause of the binding power. As an example of this, pure kaolin, which is essentially an alteration product of orthoclase, very seldom has a high binding power. Again, the much decomposed surface exposures of many of the schistose rocks do not bind so well as the fresher, deep-seated portions of the same outcrop.

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[a] U. S. Geol. Surv., Mineral Resources of the United States, 1902, pp. 666–667; Maryland Geol. Surv. Reports, 1898, v. 2, p. 164.

[b] L. W. Page, Selection of Materials for Macadam Roads, Yearbook Dept. Agr., 1900, p. 354.

PETROGRAPHIC ANALYSIS OF ROCKS FOR ROAD BUILDING.

Upon receipt of the rock sample, which, according to the specifications of this Office, should weigh not less than 30 pounds and be collected with care to represent as nearly as possible an average of the whole exposure, it is examined in a general way to determine the proper method of analysis.

Rocks consisting essentially of the carbonates of lime and magnesia (limestones, dolomites, etc.), as well as fine-grained shales and unconsolidated sedimentary deposits, such as clays, sands, gravels, etc., are analyzed chemically when necessary, whereas all other materials are prepared for microscopic examination or determined macroscopically.

The mineral composition of a rock may, under favorable conditions, be estimated with considerable accuracy by a macroscopic examination, yet for exact quantitative results the aid of a polarizing microscope and transparent thin sections of the rock are essential.

MACROSCOPIC METHOD.

The macroscopic form of analysis can be applied only to coarse-grained rock, in which the various mineral components are easily detected with the unaided eye. The approximate volumetric relations of these minerals may be determined by preparing a smooth surface of the rock sample and covering it with a transparent celluloid scale divided into 100 equal square areas and estimating the minerals present from the number of areas covered by each mineral. Any properly graduated scale can be used, but a transparent one is preferable.

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[a] U. S. Dept. Agr., Bureau of Chemistry Bul. 85.

MICROSCOPIC METHODS.

Of the various methods of microscopic analysis, probably that of Rosiwal[a] has been most generally adopted by petrographers. It consists in measuring with a micrometer scale, adjusted in the eye-piece of the microscope, the diameters of each mineral occurring along numerous lines in the thin section, care being taken to make measurements sufficient in number to equal a distance at least 100 times the average grain of the rock. The relative proportions of the diameters correspond to the volume of the minerals present.[b]

In an appendix to an interesting paper on petrographic examination of rocks[c] Professor Joly describes a simple method for determining the proportions of hard and soft constituents in rocks which, for illustrative purposes especially, should be of great practical value. The method in general consists of projecting, by means of an ordinary photographic apparatus, the slightly magnified image of the rock section upon a ground-glass screen, and covering the same with a transparent scale divided into square millimeters. On the back of the scale the outlines of the mineral constituents are traced in ink, then the divided scale is removed and the percentage of the areas occupied by the minerals is readily estimated. From a number of determinations of this kind the average mineral composition of the rock is obtained. This method assumes that the relative extent of areas is proportional to the relative abundance of the constituents, which is undoubtedly true in the more homogeneous rock types.

Owing to the large amount of material received in this laboratory it has been found necessary to perfect a more rapid method of quantitative analysis than any hitherto described.

The laboratory is equipped with an exceptionally good petrographic microscope of the latest Fuess model, which, besides the usual attachments, is provided with a revolving analyzer in the tube to aid in the determination of very low doubly refracting minerals, and a Schwarzmann scale for the measurement of optical axial angles.

Another important accessory is a detachable screw-micrometer, movable in the focal plane of the ocular by means of a drum screw, which, with the most powerful objective ($\frac{1}{12}$-inch oil immersion), records a drum-interval of 0.00004 mm. The measuring apparatus devised by Mr. L. W. Page and used for the mineral determinations consists of an ordinary fixed eye-piece having a square field divided into 100 quadratic areas. With the aid of this cross-line field, each square of which is one one-hundredth of the whole field, the relative proportions, expressed in per cent, of the minerals occupying the field can be readily determined by simply noting the number of squares covered by each mineral in turn. Averages derived from numerous examinations of this kind in various parts of the section indicate the percentage of the different minerals constituting the rock itself.

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[a] Verh. Wien. Geol. Reichs-Anst., 1898, **32**, 143.

[b] In a written communication to the writer, Prof. J. E. Wolff, of Harvard University, suggested ruling a number of fine lines in ink across the cover glass of the section and taking measurements along these lines.

[c] Royal Dublin Soc. Scient. Proc., 1903, **10**, new ser., 83–84.

The accompanying photomicrograph represents a portion of a section of augite-diorite covered by the cross-line micrometer described above.

Experience has shown that with a large majority of rock samples twenty determinations, using a magnification of 52 diameters, gives very satisfactory results. In the case of extremely fine-grained rocks, however, it is best to use a $\frac{3}{4}$-inch objective lens which enlarges 105 diameters when combined with the eye-piece micrometer.

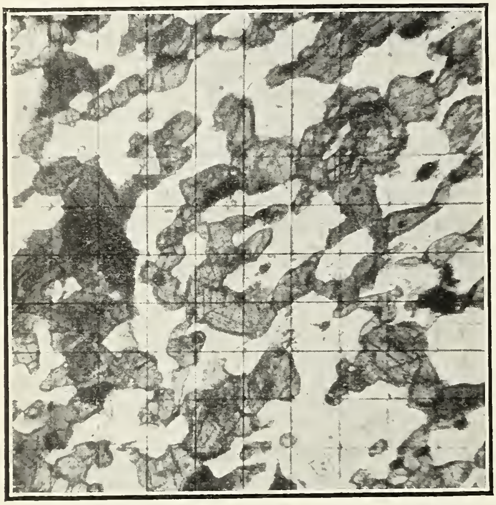

Fig. 1.—Cross-line field illustrating method of estimating minerals in thin section.

With rocks having an average grain exceeding 5 mm., or those varying greatly in texture, as in the case of porphyritic and schistose varieties, it is in some instances well to employ a 2-inch objective in combination with an ocular prepared in the same manner as that just described, but divided into only 25 square areas and magnifying 30 diameters. In the case of these exceptionally coarse-grained rocks, two or more thin sections of the same sample are examined before reliable results can be obtained.

In connection with the work carried on in the chemical laboratory it has frequently been found of importance to determine the chemical composition of a rock from the volumetric proportions of its mineral constituents as determined by the microscope. This may be done by first obtaining the relative masses of the minerals present by multiplying the percentages found by the specific gravities of the minerals and reducing the whole to one hundred, and then multiplying the products obtained by the percentages of the chemical components, reckoned as oxides, belonging to each of the minerals. Thus a quartzite consisting of 90 per cent by weight of quartz and 10 per cent orthoclase would contain 90 per cent silica (SiO_2) + 6.47 per cent silica (SiO_2) + 1.84 per cent alumina (Al_2O_3) + 1.69 per cent potash (K_2O) = 100 per cent. This computation presupposes the minerals to be definite in kind. For rocks having constituents of variable composition it will be found necessary to determine by optical means the special mineral varieties present and make use of the chemical analyses of similar varieties occurring in rocks of like character from other localities.[a] The results of the microscopic analyses are reported in the following manner: On a blank form specially prepared for the purpose, the geologic character, name, and location of the rock are indicated, and the minerals classed according to the microscopic determination, as essential, accessory, and secondary, and their general chemical composition and volumetric percentages given. Finally the color, texture, and other properties likely to be of value to road engineers are noted.

CLASSIFICATION OF MATERIAL.

As stated previously, the present systematic arrangement of rocks adopted by the Office of Public Roads has been made more from the standpoint of the road builder and engineer than from that of the geologist, although attention has been given as far as possible to the origin of the materials as well as to their mineral composition.

It will be seen from the following table that all rocks used as road materials have been separated into three general groups or classes, according to their geologic character, and that these groups are again divided into types and families.

TABLE 1.—*General classification of rocks.*

Class.	Type.	Family.
I. Igneous	1. Intrusive (plutonic)	a. Granite.
		b. Syenite.
		c. Diorite.
		d. Gabbro.
		e. Peridotite.
	2. Extrusive (volcanic).	a. Rhyolite.
		b. Trachyte.
		c. Andesite.
		d. Basalt and diabase.
II. Sedimentary	1. Calcareous	a. Limestone.
		b. Dolomite.
	2. Siliceous	a. Shale.
		b. Sandstone.
		c. Chert (flint).
III. Metamorphic	1. Foliated	a. Gneiss.
		b. Schist.
		c. Amphibolite.
	2. Nonfoliated	a. Slate.
		b. Quartzite.
		c. Eclogite.
		d. Marble.

With the exception of rocks of the second class, where chemical distinctions prevail, structural features indicating mode of origin define the type, and mineral composition the family. It will be noted later on in the description of rock-forming minerals that the family groups may be further subdivided, according to some characteristic primary constituent, into subfamilies or varieties—as, for instance, biotite-granite, hornblende-schist, etc. For a better understanding of the classification outlined above it will be necessary to give some information concerning the origin of rocks in general and explain in what manner structural features have led to the present arrangement of the material. Photomicrographs, made by Mr. B. J. Howard, illustrating the structure and mineral composition of the principal rock types are given in Plates I to X, inclusive.

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[a] Cross, Iddings, and others, Quantitative Classification of Igneous Rocks, 1903, pp. 206–207

IGNEOUS ROCKS.

All rocks of the igneous class are presumed to have solidified from a molten state, either upon reaching the earth's surface or at varying depths beneath it. The physical conditions, such as heat and pressure, under which the molten rock magma consolidated, as well as its chemical composition and the presence of included vapors, are the chief features influencing the structure. Thus, we find the deep-seated, plutonic rocks coarsely crystalline with mineral constituents well defined, as in case of granitic rocks, indicating a single, prolonged period of development (Pl. I, fig. 1), whereas the members of the extrusive or volcanic types, solidifying more rapidly at the surface, are either fine-grained or frequently glassy and vesicular, or show a porphyritic structure (Pl. IV, fig. 2). This structure is produced by the development of large crystals in a more or less dense and fine-grained ground mass, and is caused generally by a recurrence of mineral growth during the effusive period of magmatic consolidation. Rocks of this kind, exhibiting a more or less spotted appearance, are commonly described as porphyries, regardless of mineral composition, thus causing great confusion in the nomenclature. A movement in the rock magma while cooling causes frequently a banded arrangement of the minerals, or flow structure (Pl. IV, fig. 1).

There are a large number of structural terms based upon the microscopic arrangement and development of the mineral constituents which need not be enlarged upon here. Enough has been said, however, to emphasize the fact that the origin of rocks is to a large extent indicated by structural characteristics which, as will appear later, have a direct bearing on their utility as road material.

The extreme types of igneous rocks mentioned above are connected by intermediate, sometimes called hypabyssal varieties, occurring in the form of dikes, sills, intruded sheets, etc. The latter are usually wholly crystalline, of even granular or porphyritic structure, and have in this instance been classed with the intrusive rock families, to which they bear the closest mineralogical affinity. Thus pegmatite, aplite, granite-porphyry, etc., have been considered as granites, and various dioritic and syenitic dike rocks, as diorite, syenite, etc.

In the arrangement of the rock families from a mineralogical standpoint (see Table 2) it will be noted that the plutonic rock types, granite, syenite, and diorite, are represented by their equivalent extrusive varieties, rhyolite and andesite, and that diabase has been included, somewhat arbitrarily, with basalt, as a volcanic representative of gabbro. These latter rocks are of special interest, owing to their wide distribution and general use in road construction. They occur in the form of dikes, intruded sheets, or volcanic flows and vary in structure from glassy-porphyritic (typical basalt) to wholly crystalline and even granular (diabase). Their desirable qualities for road building are caused to a large extent by a peculiar interlocking of the mineral components (ophitic structure), yielding a very tough and resistant material well qualified to sustain the wear of traffic. (Pl. V, fig. 2.)

Igneous rocks vary in color from the light gray, pink, and brown of the acid granites, syenites, and their volcanic equivalents (rhyolite, andesite, etc.) to the dark steel gray or black of the basic gabbro, peridotite, diabase, and basalt. The darker varieties are commonly called trap. This term is in very general use and is derived from *trappa*, Swedish for stair, because rocks of this kind on cooling frequently break into large tabular masses, rising one above the other like steps, as may be seen in the exposures of diabase on the west shore of the Hudson River from Jersey City to Haverstraw.

SEDIMENTARY ROCKS.

The sedimentary rocks as a class represent the consolidated products of former rock disintegration, as in case of sandstone, conglomerate, shale, etc. (Pl. VII, fig. 1), or they have been formed from an accumulation of organic remains chiefly of a calcareous nature, as is true of limestone and dolomite (Pl. VI, fig. 2). These fragmental or clastic materials have been transported by water and deposited mechanically in layers on sea or lake bottoms, producing a very characteristic bedded or stratified structure in many of the resulting rocks.

In the case of certain oolitic and travertine limestones, hydrated iron oxides, siliceous deposits such as geyserite, opal, flint, chert, etc. (Pl. VII, fig. 2), the materials have been formed chiefly by chemical precipitation and show generally a concentric or colloidal structure.[a] Oolitic and pisolitic limestones consist of rounded, pealike grains of calcic carbonate held together by a calcareous cement. Travertine is the so-called "onyx marble" of Mexico and Arizona. It is a compact rock, concentric in structure and formed by the precipitation of carbonate of lime from the waters of springs and streams.

Loose or unconsolidated rock débris of a prevailing siliceous nature comprise the sands, gravels, finer silts, and clays (laterite, adobe, loess, etc.). Shell sands and marls, on the other hand, are mainly calcareous, and are formed by an accumulation of the marine shells and of lime-secreting animals. Closely associated with the latter deposits in point of origin are the beds of diatomaceous or infusorial earth composed almost entirely of the siliceous casts of diatoms, a low order of seaweed or algæ.

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[a] G. P. Merrill. Rocks, Rock Weathering, and Soils, 1897, pp. 104–114.

This unconsolidated material may pass by imperceptible gradation into representative rock types through simple processes of induration. Thus clay becomes shale, and that in turn slate, without necessarily changing the chemical or mineralogical composition of the original substance.

Such terms as flagstone, freestone, brownstone, bluestone, greystone, etc., are given generally to sandstones of various color and composition, while puddingstone, conglomerate, breccia, etc., apply to consolidated gravels and coarse feldspathic sands.

The calcareous rocks are of many colors, according to the amount and character of the impurities present.

METAMORPHIC ROCKS.

Rocks of this class are such as have been produced by the prolonged action of physical and chemical forces (heat, pressure, moisture, etc.) on both sedimentary and igneous rocks alike. The foliated types (gneiss, schist, etc.) represent an advanced stage of metamorphism on a large scale (regional metamorphism), and the peculiar schistose or foliated structure is due to the more or less parallel arrangement of their mineral components. (Pl. VIII, figs. 1 and 2). The nonfoliated types (quartzite, marble, slate, etc.) have resulted from the alteration of sedimentary rocks without materially affecting the structure and chemical composition of the original material. (Pl. X, fig. 1.)

Rocks formed by contact metamorphism and hydration, such as hornfels, pyroxene marble, serpentine, serpentineous limestone, etc., are of great interest from a petrographical standpoint, but are rarely of importance as road materials.

The color of metamorphic rocks varies between gray and white of the purer marbles and quartzites to dark gray and green of the gneisses, schists, and amphibolites. The green varieties are commonly known as greenstones or greenstone schists.

MINERAL COMPOSITION OF ROCKS USED AS ROAD MATERIAL.

In the foregoing brief discussion of the origin of rocks but passing reference has been made to their specific characteristics or mineral composition, although the latter furnishes the elements for a more exact classification than can be obtained by an examination of structural qualities alone. This is indicated in Table 2 (facing this page), in which the average mineral composition as well as the physical properties of the more important road-making rocks is given.

s of rocks for road maki

	Opal.	Titanite.	Apatite.	Scolecite.
...	......	0.1	0.1	....
...	......	0.5	0.2	....
...	......	0.3	0.1	....
...	......	0.1	0.1	....
...	......	0.5	0.5	....
...	......	0.2	0.8	....
6	......	......	......	0.1
.0	......	......	......	....
...	......	......	(*a*)	....
...	2.2	......	0.2	....
...	......	......	......	....
...	......	......	......	....
...	......	......	(*a*)	....
...	......	0.2	0.2	0.9
...	......	......	......	....
...	......	......	......	....
...	3.4	......	(*a*)	....
...	......	(*a*)	......	....
...	......	......	......	....
...	0.7	......	......	....
...	......	0.1	0.1	....
...	......	0.3	0.7	....
...	......	0.3	1.2	....
...	......	......	0.4	....
...	......	......	(*a*)	....
...	......	0.5	......	....
...	......	0.6	0.1	0.1
4	......	0.8	0.1	....
...	......	......	......	....
...	......	......	0.1	....
...	......	0.2	......	....
7	......	......	0.2	....
...	......	......	0.2	....
...	......	......	......	....

TABLE 2.—*Average mineral composition and physical properties of rocks for road making.*

No.	Rock variation.	Mineral composition, expressed in percentages.																																				Physical properties.[c]					Rock varieties.	No.
		Quartz.	Orthoclase.	Plagioclase.	Augite.	Hornblende.	Calcite.	Dolomite.	Chlorite.	Biotite.	Muscovite.	Kaolin.	Epidote.	Magnetite.	Limonite.	Microcline.	Rock glass.	Garnet.	Olivine.	Pyrite.	Hematite.	Serpentine.	Hypersthene.	Opal.	Titanite.	Apatite.	Scolecite.	Natrolite.	Zircon.	Enstatite.	Scapolite.	Nephelite.	Fluorite.	Tourmaline.	Rutile.	Sillimanite.	Topaz.	Per cent wear.	Toughness.	Hardness.	Cementing value.	Specific gravity.		
1	Granite	[b]**31.0**	**45.8**	**7.3**			0.2		0.9	**3.8**	**3.4**	1.4	0.9	0.6	0.3	**3.7**		0.1		0.1	0.2				0.1	0.1			0.1				(a)					3.5	15	18.1	20	2.65	Granite	1
2	Biotite-granite	**28.0**	**36.1**	**12.2**	1.4	0.5	0.1		0.4	**10.5**	0.4	2.3	1.7	0.8		**4.1**		0.1			0.3				0.5	0.2			0.1				(a)				(a)	4.1	10	16.8	37	2.64	Biotite-granite	2
3	Hornblende-granite	**24.0**	**40.8**	**9.7**	0.2	**11.7**	0.6		0.9	**4.7**	0.3	1.0	0.9	0.6	0.1	0.2				(a)					0.3	0.1			(a)									2.6	21	18.3	30	2.70	Hornblende-granite	3
4	Augite-syenite	4.3	**60.1**	**4.7**	**7.8**	0.8	1.4		2.4	0.7	1.1	1.0	3.0	2.1	0.1	**9.9**				0.1					0.1	0.1			0.1			0.2						2.6	10	18.1	21	2.80	Augite-syenite	4
5	Diorite	6.2	5.8	**33.0**	0.1	**31.0**	1.1		1.9	2.3		7.2	3.7	3.1	0.1					0.6					0.5	0.5			0.1									2.9	21	18.1	11	2.90	Diorite	5
6	Augite-diorite	1.1	**22.0**	**29.6**	**14.8**	**13.3**	0.3		4.4	4.5		3.5	0.1	5.2						0.1					0.2	0.8			0.1									2.8	19	17.7	65	2.98	Augite-diorite	6
7	Gabbro	0.7		**42.7**	**20.3**	**11.0**	0.3		1.4	3.5		7.2	0.6	2.3	0.1				1.1			0.4	1.6				0.1			0.7								2.8	16	17.9	20	3.00	Gabbro	7
8	Peridotite				**16.0**	0.6								**30.6**	0.3				**5.0**			27.5	**20.0**															1.0	12	15.2	28	3.00	Peridotite	8
9	Rhyolite	**38.0**	**42.1**	**3.0**		1.2	2.2		1.3	2.0	1.8	1.6	2.7	1.8	0.7	0.1	0.6			0.2	0.7					(a)			(a)									3.7	20	17.8	18	2.40	Rhyolite	9
10	Andesite	9.7		**45.7**	**8.6**	1.9	7.3		6.8		1.1		8.5	3.2	1.8		3.0							2.2		0.2												4.7	11	13.7	180	2.50	Andesite	10
11	Fresh basalt			**36.1**	**45.0**	0.1	0.1		0.2	0.1				4.0	0.1		**8.2**		**4.3**			1.8																3.3	23	17.1	111	2.90	Fresh basalt	11
12	Altered basalt			**28.6**	**21.9**		3.4		10.2			10.3	5.1	2.9	0.2		**10.3**		0.5			2.9						0.7										5.3	17	15.6	249	2.75	Altered basalt	12
13	Fresh diabase			**48.8**	**14.4**		0.1		0.9	0.4	(a)	0.1		4.2					0.8	(a)		0.3				(a)												2.0	20	18.2	19	3.00	Fresh diabase	13
14	Altered diabase	0.6		**37.4**	**20.2**	7.5	1.0		13.0	1.3		3.7	4.4	6.1	0.3				1.6	0.2		0.9			0.2	0.2	0.9	0.5										2.5	21	17.5	156	2.95	Altered diabase	14
15	Limestone	6.4					**82.3**	6.0							1.7					3.4	0.2																	5.6	10	12.7	60	2.70	Limestone	15
16	Dolomite	8.6	0.4				7.5	**78.6**				0.9			1.7					1.2	1.1																	5.7	10	10.8	12	2.70	Dolomite	16
17	Sandstone	**71.2**	3.1	0.3			1.1		0.8	0.3	4.4	1.6	(a)	0.5	6.1			0.6		0.3	6.2			3.4		(a)			0.1					(a)	(a)			6.9	20	17.1	90	2.55	Sandstone	17
18	Feldspathic sandstone	**12.1**	**24.3**	0.2			0.1		3.7	0.9	1.8	20.6	0.9	0.8	4.2										(a)				0.1					(a)				4.3	17	15.3	119	2.70	Feldspathic sandstone	18
19	Calcareous sandstone	**39.6**	**17.3**	0.3			**35.3**		3.8	0.2	0.3			0.5	2.4			0.1		0.1									0.1									7.4	15	8.3	101	2.66	Calcareous sandstone	19
20	Chert	**91.2**	0.1				0.9		0.1	(a)	0.2	0.7		0.1	2.0			0.7		0.1	0.2			0.7										(a)				10.8	15	19.1	27	2.50	Chert	20
21	Granite-gneiss	**37.2**	**41.1**	2.5		0.4	0.3		1.9	**4.7**	**4.9**	1.1	1.6	0.7	0.2	2.9		0.1		0.1					0.1	0.1			0.1							(a)		3.8	12	17.7	26	2.68	Granite-gneiss	21
22	Hornblende-gneiss	**11.1**	**18.4**	1.0		**53.1**				1.9	3.5	0.3	2.3	2.4	0.2	3.3		0.3		0.6					0.3	0.7			0.3									4.7	16	17.1	30	3.02	Hornblende-gneiss	22
23	Biotite-gneiss	**10.9**	**33.2**	0.9		0.1	0.3		1.0	**12.9**	1.5	0.5	1.5	1.7	0.2	2.9		0.7		0.1					0.3	1.2			0.1									3.2	19	15.5	11	2.66	Biotite-gneiss	23
24	Mica-schist	**39.3**	**14.8**	1.4			2.1		1.3	**14.6**	**19.2**	0.2	4.5	1.4	(a)			0.3		0.4	(a)					0.4			0.1									4.1	10	17.3	30	2.80	Mica-schist	24
25	Biotite-schist	**27.3**	**13.7**	3.4	0.4	10.3			(a)	**38.7**	0.2		1.0	1.3		0.2		2.0		1.4						(a)			0.1									4.0			16	2.70	Biotite-schist	25
26	Chlorite-schist	**19.9**	**10.1**	3.3			1.2		**36.3**	0.2	4.6		**20.4**	2.6	0.4					0.5					0.5													4.2			24	2.90	Chlorite-schist	26
27	Hornblende-schist	**11.3**	4.7	6.9	1.0	**62.5**	0.5		0.7	0.5	0.4	0.1	4.7	2.1	0.4	0.4		2.4		0.3					0.6	0.7	0.1		(a)		0.3							3.7	21	16.5	63	3.00	Hornblende-schist	27
28	Amphibolite	3.1	2.9	6.5		**71.0**	0.2			1.1			**10.7**	1.9	0.2			0.1					1.4		0.8	0.1												2.9	11	19.0	29	3.00	Amphibolite	28
29	Slate	**25.9**		0.1			2.4			0.9	**63.8**		2.4	2.1	2.1					0.2									0.1					(a)				1.7	12	11.5	102	2.80	Slate	29
30	Quartzite	**86.2**	1.9	0.2		0.8	1.3		0.8	3.7	2.2		1.0	0.3	1.0			0.1			0.3					0.1			0.1					(a)				2.9	19	18.1	67	2.70	Quartzite	30
31	Feldspathic quartzite	**46.3**	**33.7**	1.2			2.1		5.7	1.1	4.4	0.6	2.3	0.4	1.5						0.5				0.2				(a)					(a)	(a)			3.2	17	18.3	21	2.70	Feldspathic quartzite	31
32	Pyroxene quartzite	**36.0**	3.6	**25.1**	**22.2**									4.0				1.9		0.3			6.7			0.2												2.3	27	18.6	17	3.00	Pyroxene quartzite	32
33	Eclogite	5.0		**28.8**	**14.5**	1.8	1.2		0.8	4.5				4.7				**38.4**		0.1						0.2												2.1	31	17.1	21	3.30	Eclogite	33
34	Epidosite	**10.8**	1.8			**13.6**							**61.9**	1.9	0.9														0.1									3.6	16	16.0	37	3.03	Epidosite	34

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[a] Trace.

[b] Figures in bold type indicate the essential minerals which are characteristic of the rock variety.

[c] For explanation of figures representing physical properties, see text, pages 23-26.

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It will be noted that the order followed in the classification in Table 1 has been maintained in the present arrangement of the material. Thus, 1 to 8 embrace the plutonic igneous, 9 to 14 the volcanic igneous, 15 to 20 the sedimentary, and 21 to 34 the metamorphic rocks or crystalline schists.

The mineral components themselves have been given in the order of their prominence as rock-forming constituents and their volumetric percentages placed in vertical columns adjoining the names of the corresponding rock varieties. By consulting a table of this kind it is possible to determine at a glance the average mineral composition of any road-making rock, together with its physical character and position in the general classification.

The physical properties, per cent of wear, toughness, hardness, specific gravity, and cementing value have been obtained by averaging the results of the mechanical tests made in the testing laboratory of this Office. They are only in a very general way characteristic of any individual rock sample, but will serve as a means for comparing the various rock types.

Before undertaking a comparison of this kind, however, it will be necessary to consider in some detail the physical and chemical properties of the essential rock constituents. These minerals may be conveniently separated into two groups: (1) Primary minerals, occurring as original constituents of the rock, and (2) secondary minerals, derived from the former through processes of alteration. Where the primary minerals occur as characteristic components of the rock varieties, they are printed in heavy type in the table.

PRIMARY MINERALS.

In a strict interpretation of the term, only the original components of igneous rocks can be regarded as primary, yet in the following description the essential constituents of such rocks as have been formed by sedimentation or by metamorphic agencies will be included in the same category.

As constituents of igneous rocks the primary minerals have separated from a more or less completely fused magma and have reached a maximum degree of perfection in their crystalline development and chemical constitution, whereas their secondary derivatives are to a large extent indefinite in form and chemical composition. In the case of certain rock magmas (basalt, rhyolite, andesite, etc.), where the rate of cooling has been very rapid, a glass base (rock glass) is frequently left after crystallization has ceased. This glass occurs either in insignificant quantities, simply filling the interstices of the rock, or it may constitute the ground mass and, in exceptional cases, even the entire rock as in obsidian, pitchstone, etc.

In the following table are given the essential primary minerals occurring in rocks used for road making, together with their approximate chemical composition and volumetric percentages:

TABLE 3.—*Primary mineral constituents of rocks used for road making.*

Name.	Chemical composition.	Volumetric percentage.
Quartz	Silica	22.6
Orthoclase (microcline)	Silicate of alumina and potash	14.9
Plagioclase	Silicate of alumina, lime, and soda	14.5
Augite	Silicate of lime, magnesia, iron, and alumina	8.3
Hornblende	Silicate of lime, magnesia, iron, and alumina	7.2
Calcite	Carbonate of lime	6.1
Dolomite	Carbonate of lime and magnesia	4.8
Biotite	Hydrous silicate of alumina, iron, magnesia, and potash	2.8
Muscovite	Hydrous silicate of alumina and potash	2.6
Magnetite	Magnetic oxide of iron	2.0
Rock glass	Variable	0.7
Garnet	Silicate of iron, alumina, and lime	0.5
Olivine	Silicate of magnesia and iron	0.5
Pyrite	Disulphide of iron	0.4
Hematite	Oxide of iron	0.4
Hypersthene	Silicate of iron and magnesia	0.2
Titanite	Titano-silicate of lime	0.1
Apatite	Phosphate of lime	0.1
Zircon	Silicate of zirconia	0.1

Quartz is without doubt the commonest and most widely distributed mineral in the earth's crust and is found in greater or less abundance in all kinds of road material, excepting the more basic igneous rocks. It has a hardness of 7, according to the Mohs scale,[a] and specific gravity of 2.6. Although crystallizing in veins and open fissures in well-developed hexagonal prisms with pyramidal terminations, it has, as a rock-forming constituent, rarely a definite crystal form, and is recognized in the hand sample chiefly by a glass-like fracture, vitreous luster, and lack of cleavage. As a constituent of igneous rocks quartz is generally the last mineral to crystallize, and is in some instances intergrown with feldspar in such a manner as to resemble Hebraic characters, thus producing a graphic or pegmatitic structure characteristic of certain varieties of granite, granite-porphyry, and pegmatite.

In acid igneous rocks, such as rhyolite, quartz-porphyry, etc., the porphyritic constituents (phenocrysts) are to a large extent quartz crystals, occasionally with regular outlines (Pl. IV, fig. 1), but more frequently indented and rounded in a peculiar manner by the corrosive action of the rock magma.

As a secondary mineral, quartz appears in cryptocrystalline aggregates (chalcedony) frequently associated with opaline silica, in the fissures and holes formed by escaping vapors (amygdaloidal cavities) of basaltic and rhyolitic lavas, or it occurs as a cementing material in sedimentary (sandstone, chert, etc.) and metamorphic rocks (quartzite, etc.).

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[a] This scale as described in Merrill's Rocks, Rock-weathering and Soils, p. 12, is based upon the relative hardness of the following minerals arranged in ascending order: (1) Talc, (2) gypsum, (3) calcite, (4) fluorite, (5) apatite, (6) orthoclase, (7) quartz, (8) topaz, (9) corundum, and (10) diamond.

Orthoclase (microcline) and *plagioclase* comprise a very common group of minerals known as feldspar. They are prominent in all rock types, excepting some varieties of limestones, quartzites, and ultrabasic igneous rocks (peridotites). They have a hardness of 6 to 6.5 with a specific gravity of 2.5 to 2.7, and crystallize in short prismatic, tabular or lath-like forms (Pl. IV, fig. 2) with well-defined cleavage and characteristic twinning. The bright, reflecting surfaces of the large transparent minerals common in coarse-grained rocks and recent lavas are cleavage planes of feldspar that intersect at an angle of 90 degrees, in the case of orthoclase, and approximately the same for plagioclase. The latter mineral is readily distinguished from orthoclase by a very fine, parallel striation on basal cleavage surfaces, caused by the development of twinning lamellæ about normal to these planes.

The feldspars have been divided crystallographically into two classes: (1) Those occurring in the monoclinic system, to which orthoclase (potash feldspar) belongs, and (2) others crystallizing in triclinic forms, including microcline, anorthoclase, and members of the soda-lime or plagioclase group. The latter series, beginning with albite, pure soda-alumina silicate, and terminating in anorthite, pure lime-alumina feldspar, include intermediate varieties, such as oligoclase, andesine, labradorite, and bytownite, which contain lime and soda in varying proportions, depending on the chemical composition of the rocks in which they occur.

In averaging the mineral composition of road material (Table 2), no attempt has been made to subdivide these plagioclase feldspars, although in the analyses of individual samples the proper specific varieties are usually reported. It may be sufficient to state here that in acid igneous rocks, ranging in silica from 55 to 75 per cent, such as granite, syenite, diorite, rhyolite, and andesite, as well as in sedimentary rocks and crystalline schists, the prevailing plagioclase is oligoclase or andesine, whereas in the basic gabbro, diabase, and basalt, containing from 40 to 55 per cent silica, the common varieties are labradorite or bytownite. Orthoclase and microcline are normally confined to the acid igneous rocks, sandstones, siliceous schists, and gneisses.

The feldspars vary from colorless transparency to gray, yellowish gray, pink, or occasionally green (amazon-stone). They are usually the first minerals in the rock to undergo decomposition, and in consequence are frequently opaque and more or less completely replaced by secondary products, such as kaolin, muscovite, natrolite, etc. (Pl. I, fig. 2.)

Hornblende is a very prominent constituent of igneous rocks, metamorphic schists, and gneisses. Under the general term amphibole are included the principal varieties of hornblende, which may be divided, according to chemical composition and physical properties, into two groups: (1) Actinolite (tremolite), composed essentially of the silicate of lime, magnesia, and ferrous iron, and occurring generally in long prismatic or fibrous forms; and (2) common hornblende, rich in iron peroxide and alumina and having usually a dark-green color and short prismatic development. (Pl. II, fig. 1.)

Actinolitic amphiboles vary in color from white to green, according to the quantity of iron present, and are the essential components of certain metamorphic limestones and schists. Common hornblende may be readily detected in most rock samples by its green, brownish-green, or black color, prismatic form, and characteristic prismatic cleavage produced by the intersection of the cleavage planes at an angle of about 124 degrees. (Pl. IX, fig. 2.) It varies in hardness from 5 to 6 and in specific gravity from 2.9 to 3.7 and forms a prominent part in hornblendic varieties of granite, diorite, syenite, gabbro, andesite, and basalt, as well as in amphibolites, amphibolite-schists, and gneisses. (Pl. IX, fig. 2.) Secondary hornblende (uralite) is a molecular alteration of augite. The principal decomposition products of hornblende are chlorite, epidote, calcite, quartz, and limonite.

Augite occurs as an essential constituent in nearly all varieties of basic igneous rocks, pyroxene-bearing schists, quartzites, and eclogites. In the hand sample it is frequently distinguishable from hornblende by a nearly rectangular prismatic cleavage (Pl. II, fig. 2), in contrast to the obtuse intersection angles of the amphibole cleavage. In point of hardness, color, specific gravity, and chemical composition, hornblende and augite are essentially identical. Thus we have the lighter colored varieties of augite, comprising the silicates of lime, magnesia, and ferrous iron (diopside, malacolite, salite), corresponding to light-green actinolite and tremolite, and the darker colored, containing alumina and ferric iron in excess (augite proper and basaltic augite), comparable with the dark-green and black amphiboles. The collective term pyroxene embraces the above varieties of augite, as well as some others crystallizing in the orthorhombic system (Pl. III, fig. 1), and composed essentially of the silicates of iron and magnesia (enstatite, bronzite, and hypersthene). The latter are, however, rarely abundant in rocks used as road material and need not be further considered here. The decomposition products of pyroxenes are similar to those derived from the hornblendes, with the exception of the orthorhombic varieties, where the secondary minerals are mainly serpentine (bastite) or talc.

Both hornblende and augite are very hard and tough and have an important bearing on the physical properties of many rock types (diorite, diabase, básalt, etc.).

Calcite and *dolomite* have been regarded as primary minerals only where they occur as essential components of limestones and dolomites. They vary in hardness from 3 for calcite to 3.5 to 4 for dolomite and in specific gravity from 2.6 to 2.9.

The carbonates are readily recognized by their perfect rhombohedral cleavage (Pl. VI, fig. 1), softness, and glass-like luster.

In the case of many fine-grained, loosely textured limestones the calcite is in the form of a soft, white powder, easily abraded by the finger nail, while more compactly crystalline dolomites and marbles, on the other hand, are quite tough and offer considerable resistance to wear.

A rapid method for distinguishing between dolomite and calcite is by means of cold dilute hydrochloric or nitric acid. It will be noted at once that calcite dissolves rapidly under strong ebullition of carbonic-acid gas, while dolomite is very slowly acted upon and the effervescence is scarcely perceptible. In hot acid, however, both minerals are dissolved with about equal rapidity.

Muscovite and *biotite* belong to an important group of minerals known as mica. They are found in varying proportions in nearly all kinds of road stones, especially in the acid igneous rocks and micaceous schists and gneisses. They are readily recognized in coarse-grained granitic and schistose rocks by their thin tabular form, often with hexagonal outline, and by a perfect basal cleavage which enables the crystals to be easily separated into thin, elastic plates. (Pl. III, fig. 1.) The hardness of mica varies from 2 to 3 and the specific gravity from 2.7 to 3.2.

Muscovite, or white potash mica, is characteristic of the granites, gneisses, and coarser schists, producing to a large extent the laminated or schistose structure of the latter rocks. (Pl. VIII, fig. 2.) In certain fine-grained schists and slates (phyllites) it is known as sericite and occurs in the form of exceedingly fine leaves or shreds, imparting a peculiar silky luster to the cleavage planes of these rocks.

Biotite is a dark, iron-bearing mica and one of the first constituents of igneous rocks to crystallize, usually in idiomorphic forms (Pl. III, fig 1). As a component of metamorphic rocks, however, the crystal boundaries are frequently lost and the mineral appears as irregularly bounded leaves or films drawn out in the direction of the schistosity.[a] (Pl. VIII, fig. 1.)

Muscovite, although a common alteration product of feldspar, is itself rarely affected by atmospheric alteration, while biotite, on the contrary, is rarely secondary and relatively quickly replaced by chlorite, calcite, epidote, limonite, etc.

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[a] Rosenbusch, Mikroskopische Physiographie der Mineralien und Gesteine, 4th ed., v. 1, pt. 2, p. 258.

Magnetite, *hematite* (ilmenite), and *pyrite* occur in one form or another in nearly all varieties of road material, yet very rarely in sufficient quantities to be classed as essential constituents. (Pl. III, fig. 2.) They are composed chemically of the oxides of iron, with varying amounts of titanium (magnetite, hematite) and iron disulphide (pyrite). Magnetite, having a hardness of 5.5 to 6 and specific gravity of about 5, is the most important member of the group. It is a common accessory component of basic igneous and metamorphic rocks and is readily recognized by a brilliant metallic luster, iron black color, and the octohedral development of its crystals. (Pl. X, fig. 2.) In certain varieties of basalt and andesite rich in rock glass, magnetite frequently assumes delicate spear-like forms (skeleton crystals), and is occasionally intimately intergrown with titaniferous iron oxide (ilmenite). Magnetite weathers rust brown, owing to the formation of limonite, or, when titaniferous, is more or less completely replaced by leucoxene (titanite).

Hematite in the form of minute scales of a blood-red color is the prevailing coloring pigment of pinkish or flesh-colored granites and other siliceous rocks, and also occurs, usually associated with limonite, as the cementing material of many sandstones (Pl. VII, fig. 1), as well as the coloring matter in clay and other residual products.

Pyrite (iron pyrites) is a very common iron ore in road material of all kinds. As a component of igneous rocks it is usually of primary origin, while in sedimentary and metamorphic rocks it is generally regarded as secondary. It has a hardness of 6 to 6.5, specific gravity of 4.9 to 5.2, and is determined by a strong metallic luster, brass-yellow color, and the characteristic decomposition products, limonite and hematite, which frequently entirely replace it, forming perfect pseudomorphs.

Garnet occurs as a principal ingredient in eclogite, a rarely used road material, although it is frequently found in subordinate quantities in granites, cherts, sandstones, and crystalline schists. It is extremely hard (7 to 7.5) and crystallizes generally in the form of brown or reddish-brown dodecahedrons or irregular grains. (Pl. X, fig. 2.) Garnet is without regular cleavage and rarely exhibits indications of atmospheric weathering or alteration.

Olivine (chrysolite) is present as an essential constituent in certain varieties of peridotite and basalt and occurs frequently in variable proportions in gabbro and diabase. Its hardness is 6.5 to 7 and specific gravity about 3. Olivine is characterized by a bright, vitreous luster, olive or brownish-green color, and orthorhombic crystal form. It is distinguished from augite and hornblende by irregular fracture and rectangular cleavage, usually emphasized by incipient serpentinous alteration (Pl. V, fig. 1), as well as by a tendency to segregate in peculiar mineral clusters or large crystal aggregates (olivine bombs). Chrysolite offers but slight resistance to atmospheric decomposition and is usually replaced to a greater or less extent by serpentine, frequently accompanied by limonite, magnetite, calcite, or dolomite.

Titanite, *apatite*, and *zircon* are widely distributed as accessory constituents through many types of road material, but the crystals are rarely of sufficient size to be recognized without the aid of the microscope.

The remaining accessory minerals, *enstatite*, *scapolite*, *nephelite*, *tourmaline*, *rutile*, *sillimanite*, *fluorite*, and *topaz*, are of such rare occurrence in road material (0.1 per cent) that they need not be further discussed here.

SECONDARY MINERALS.

Where minerals have been formed after the consolidation of the rock as a whole, chiefly through processes of atmospheric weathering and hydrometamorphism of the primary constituents, they have been considered as secondary, and the rocks containing them in appreciable quantities described as weathered or altered.

These secondary compounds are essentially hydrated silicates of the commoner metals, and, although constituting but an insignificant part in the total composition of road material, have in certain instances a marked influence on the physical properties of the rocks. Their approximate chemical composition and volumetric percentages are shown in the following table:

TABLE 4.—*Secondary mineral constituents of rocks used for road making.*

Name.	Chemical composition.	Volumetric percentages.
Chlorite	Hydrous silicate of magnesia, iron, and alumina	3.5
Kaolin	Hydrous silicate of alumina	2.4
Epidote	Hydrous silicate of lime, iron, and alumina	2.2
Calcite	Carbonate of lime	1.4
Limonite	Hydrated oxide of iron	0.9
Serpentine	Hydrous silicate of magnesia and iron	0.3
Opal	Hydrated silica	0.2
Scolecite	Hydrous silicate of alumina and lime	0.1
Natrolite	Hydrous silicate of alumina and soda	0.1

Chlorite is a very common decomposition product in all varieties of rock, more especially in diabase, basalt, andesite and gabbro, as well as a metamorphic constituent of schists and gneisses. In the latter rock types it occurs frequently in the form of well-developed plates or folia, closely resembling mica (Pl. IX, fig. 1), but may be readily distinguished from this mineral by its dark-green color, inconsiderable hardness (2 to 2.5), and solubility in acids. Chlorite appears usually in the form of fibrous aggregates as a replacement product of augite, mica, and hornblende, or it fills veins and amygdaloidal cavities in volcanic rocks, and can be determined only by a careful microscopic examination. To a very indefinite chloritic mineral (viridite) is due the green color of many altered igneous rocks, the so-called greenstones of the older geologists.

Epidote is widely distributed through nearly all altered rock types containing its chemical elements, and is generally associated with chlorite as an alteration product of augite, hornblende, biotite and feldspar. It also occurs as an essential component of certain nonfoliated or massive metamorphic rocks, such as epidosite, epidote quartzite, etc., always in the form of hard, angular grains or massive aggregates of yellowish green color.

Under the general term epidote have been included zoisite and allanite, minerals of similar character though differing somewhat in composition and in physical properties.

Serpentine (including *talc*) is another important secondary mineral resembling chlorite very closely in composition and mode of origin. It is soft (3 to 4), unctuous, and appears in the form of mottled green, fibrous (chrysotile), or foliated crystal aggregates (antigorite), replacing nonaluminous pyroxene, amphibole and olivine or filling veins in basic plutonic rocks (peridotites).

Kaolin is perhaps the most widely distributed product of rock decay, yet in many instances it is impossible, by microscopic methods alone, to distinguish it from the secondary muscovite derived from feldspar. Kaolin crystals in the form of thin plates, divergent leaves, or opaque, earthy aggregates, are frequently noticeable in weathered feldspathic road material, and indicate generally a weakening of the original rock texture. (Pl. I, fig. 2.) Kaolin comprises much of the so-called argillaceous matter in sandstones, limestones, shales, etc., and forms the body of clay and other plastic sedimentary deposits.

Calcite, including dolomite, is a common secondary mineral in igneous and metamorphic rocks containing silicates of lime and magnesia. It is either formed in place, as the result of atmospheric weathering of these minerals, or it may be brought in solution from extraneous sources and deposited along rifts or in veins and other rock cavities in the form of irregular grains or well-developed crystals.

The carbonates also form an important cementing material in volcanic tuffs, breccias, and various kinds of sedimentary rocks (sandstones, conglomerates, shales, etc.). They are always recognized by effervescence on treatment with dilute hydrochloric acid.

Limonite is a rather soft (5 to 5.5), noncrystalline, yellowish-brown iron ore containing 14 per cent water, and is formed by direct hydration of the oxides (hematite, magnetite) and sulphides of iron (pyrite, marcasite, etc.), as well as by the decomposition of ferruginous minerals generally. It is usually in an earthy or massive condition, and serves frequently as cementing material in sandstones (Pl. VII, fig. 1) and other sedimentary rocks.

Opal is a rare, amorphous mineral with about the hardness of quartz, and occurs in veins and irregular interstitial spaces in decomposed eruptive rocks (trachyte, andesite, basalt, etc.), or with chalcedonic silica, in some cherts (Pl. VII, fig. 2) and novaculites. In certain high-binding sandstones opaline silica forms the principal cementing material, rendering these rocks of special value as road materials.

Natrolite and *scolecite* are colorless or grayish-white zeolitic minerals quite alike in general appearance. They are found in decomposed varieties of basic igneous rocks, generally in the form of fibrous or acicular aggregates replacing the feldspar constituents.

PHYSICAL PROPERTIES OF ROAD MATERIALS.

From what has been said it is apparent that many kinds of minerals, associated in different ways and occurring usually in various stages of alteration, enter into the composition of rocks used as road materials. It will be of interest now to consider briefly the physical properties of these materials from a road-making standpoint, and to determine what bearing, if any, mineral composition and rock structure may have on them.

The physical properties selected for this investigation, per cent of wear, hardness, toughness, cementing value, and specific gravity have already been described at length in a bulletin of the Department,[a] from which the following general information has been taken:

Percentage of wear represents the amount of material under 0.16 cm. in diameter lost by abrasion from a weighed quantity of rock fragments of definite size. It is determined in the following manner: The rock sample is broken into pieces that will pass through a 2.4-inch ring but not through a 1.2-inch ring, and after being thoroughly cleansed, dried, and cooled, 5 kg. are weighed and placed in a cast-iron cylinder (34 cm. deep by 20 cm. in diameter) closed at one end and having a tight-fitting iron cover at the other. This cylinder is one of four attached to a shaft so that the axis of each is inclined at an angle of 30° with that of the shaft. These cylinders are revolved for five hours at the rate of 2,000 revolutions per hour, during which the stone fragments are thrown from one end of the cylinder to the other twice in each revolution. At the end of the five hours the machine is stopped, the cylinders opened, and their contents poured into a basin, in which every stone is carefully washed to remove any adherent detritus. This abraded material is then thoroughly dried, and from the amount lost below 0.16 cm. the per cent of wear is estimated.

Hardness is the resistance which a material offers to the displacement of its particles by friction, and varies inversely as the loss in weight by grinding with a standard abrasive agent. The test is made in the following manner: The test piece in the form of a cylinder about 3 inches in length by 1 inch in diameter is prepared by an annular core drill and placed in the grinding machine in such a manner that the base of the cylinder rests on the upper surface of a circular grinding disk of cast iron, which is rotated in a horizontal plane by a crank movement. The specimen is weighted so as to exert a pressure of 250 grams per square centimeter against the disk, which is fed from a funnel with sand of about 1½ mm. in diameter. After 1,000 revolutions the loss in weight of the sample is determined and the coefficient of wear obtained by deducting one-third of this loss from 20.

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[a] U. S. Dept. Agr., Bureau of Chemistry, Bul. No. 79.

Toughness as here understood is the power possessed by a material to resist fracture by impact. The test piece is a cylindrical rock core similar to that used in determining hardness, and the test is made with an impact machine constructed on the principle of a pile driver. The blow is delivered by a hammer weighing 2 kg., which is raised by a sprocket chain and released automatically by a concentric electromagnet. The test consists of a 1 cm. fall of the hammer for the first blow and an increased fall of 1 cm. for each succeeding blow until failure of the test piece occurs. The number of blows required to cause this failure represents the toughness.

The cementing value, or binding power of a road material, is the property possessed by a rock dust to act as a cement on the coarser fragments comprising crushed stone or gravel roads. This property is a very important one and is determined approximately as follows: One kg. of the rock to be tested is broken sufficiently small to pass through a 6 mm. but not a 1 mm. screen. It is then moistened with a sufficient amount of water and placed in an iron ball mill containing two chilled iron balls weighing 25 pounds each and revolved at the rate of 2,000 revolutions per hour for two hours and a half, or until all the material has been reduced to a thick dough, the particles of which are not above 0.25 mm. in diameter. About 25 grams of this dough is then placed in a cylindrical metal die, 25 mm. in diameter, and by means of a specially designed hydraulic press, known as a briquette machine, is subjected to momentary pressure of 100 kg. per square centimeter. Five of the resultant briquettes, measuring exactly 25 mm. in height, are taken out and allowed to dry for 12 hours in air and 12 hours in a hot oven at 100° C. After cooling in a desiccator they are tested by impact in a machine especially constructed for the purpose. This machine is somewhat similar to that used in determining the hardness and the blow is about the same, excepting that it is given by a 1 kg. hammer and the distance of drop does not exceed 10 cm.[a]

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[a] This Office has under construction an improvement upon this impact machine whereby the blow is delivered by a pendulum movement of the hammer instead of a vertical movement.

The standard fall of the hammer for a test is 1 cm., and the average number of blows required to destroy the bond of cementation in the five briquettes determines the cementing value.

The specific gravity is the weight of the material compared with that of an equal volume of water, and is obtained by dividing the weight in air of a rock fragment by the difference of its weight in air and water. Given the specific gravity, the weight per cubic foot of a rock is found by multiplying this value by 62.5 pounds, the weight of a cubic foot of water.

CORRELATION OF PHYSICAL PROPERTIES WITH MINERAL COMPOSITION.

Interesting experiments bearing on the wearing qualities of road metal have been recently carried on in England by Lovegrove,[a] and the results obtained point unmistakably to the fact that the loss by attrition is to a large extent conditioned by the texture, mineral composition, and state of freshness of the minerals. In the general conclusions [b] the author emphasizes the fact that the hardest and toughest stones are those combining an abundance of quartz (hardness 7) with a dense, fine-grained texture and that the best rock structures for wear are micographic, microgranitic, and ophitic, characterizing certain granites, granite-porphyries, and diabase. Porosity produced by fracture of the rock in place, a quality found in slates, and insufficient cementing substance condemn the material, as does also the appreciable development of secondary minerals, especially in the zone of surface weathering. On the other hand, the presence of a deep-seated alteration product (uralitic hornblende) and the breaking down of large crystal units (feldspar) into an aggregate of smaller secondary crystal grains have a decided tendency to strengthen the rock. These results have been in a general way confirmed by the present investigation, although no attempt has been made to compare individual rock samples, as was done by Lovegrove. Thus it will be seen (Table 2) that the average per cent of wear of fresh igneous and metamorphic rocks and those rich in secondary hornblende (gabbro, diorite, and syenite) is appreciably less than that of weathered varieties containing an excess of kaolin, chlorite, calcite, serpentine, etc., as in case of decomposed granite, peridotite, andesite, and basalt, while all yield better results than limestones, dolomites, calcareous sandstones, and cherts.

If similar investigation is carried further, a relation is found to exist between other physical properties and the structure and mineral composition of rocks. This will be brought out in a brief discussion of the three classes of road rocks given in Table 2 (facing p. 14).

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[a] Surveyor, 1905, 28, Nos. 721–728.

[b] Ibid., 1905, 28, 773.

In the case of the igneous rocks it will be noted that the plutonic types with granitic granular structure (granite, syenite, diorite, and gabbro) are, as a rule, harder but inferior in toughness to their volcanic equivalents (rhyolite, basalt, and diabase). This is due to the more fully crystalline condition and coarser grain of the plutonic rocks. In the case of the volcanic types a compact crystal intergrowth and fine grain tend to increase the toughness rather than hardness of the material. The deleterious effect of atmospheric decomposition on rock texture is especially noticeable in the case of peridotite, andesite, and altered basalt, where the indifferent results of the physical tests, excepting cementing value, may be directly ascribed to the presence of such soft secondary minerals as kaolin, serpentine, calcite, chlorite, etc. As has already been stated in a previous paragraph, the cementing value is as a rule found more highly developed in the igneous rocks which contain alteration products than in their unaltered varieties. This is especially true in the case of diabase and basalt, rocks very similar in origin and mineral composition. Continuing a step further, we note a marked decrease in toughness, hardness, and resistance to wear in the altered varieties of both these rock types over their fresher representatives. This is in line with what has already been said and indicates that the presence of secondary minerals in appreciable quantities, whether because of their softness or their indefinite semicrystalline condition, weakens the original mineral bond and tends to destroy the primary texture of the rock, while at the same time furnishing the elements for a high binding quality in the rock powder. Valuable results bearing on the decomposition of rock powders by water have been obtained by Dr. A. S. Cushman in a series of interesting experiments carried on in the chemical laboratory of this Office. Doctor Cushman has shown that hydrolysis takes place in case of many rock powders the moment they are wet, thus producing secondary products (hydrated silicates) of a colloidal nature which greatly increase the binding power.[a] This points finally to the conclusion that the mineral analysis of igneous rocks, besides providing a convenient means for comparison and classification, serves to a certain extent as a measure of their physical properties.

Considering the next important group of road-making rocks, we notice here also a marked coincidence in mineral composition and physical properties. The soft and nonresistant calcareous rocks (limestones, dolomites, and calcareous sandstones), composed largely of calcite and dolomite, are, as would be expected, inferior in hardness, toughness, and wearing qualities to the more siliceous sandstones and cherts.

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[a] U. S. Dept. Agr., Office of Public Roads, Cir. 38, Bul. 28.

The low cementing value of chert obtained by laboratory tests is not in every case in accordance with that developed by this rock under traffic.[a] In discussing the origin of road material (p. 13), it has been stated that chert or flint belongs to that class of sedimentary rocks whose mineral components have been formed largely by chemical precipitation, and were originally of a colloidal or amorphous nature. The highly fractured condition of many cherts is probably due in a large measure to shrinkage caused by a decrease in volume in passing from an amorphous to a crystalline state. Although no experiments have as yet been made on the solubility of this material, it seems to the writer very probable that the dissolving action of road waters on finely divided chert dust is relatively high and that the high binding power of some of these rocks is caused by hydrated opaline silica resulting from a decomposition of this kind. The fact that in certain localities surface flints are superior to quarry flints for road making[b] is suggestive in this connection.

The last important group of road materials to be considered, the metamorphic rocks, show a marked resemblance in mineral composition to certain types of igneous and sedimentary rocks with which they may be genetically connected. Thus, granite, diorite, diabase, sandstone, limestone, etc., find their metamorphic equivalents in gneiss, hornblende-schist, chlorite-schist, quartzite, marble, etc. It will be noted, furthermore, that the minerals produced by metamorphism are mainly epidote, hornblende (uralite), chlorite, quartz, and mica, whereas the products of atmospheric weathering (kaolin, calcite, limonite, and zeolites), conducive to textural weakness in other rock types, are present only in very slight quantities. To the scarcity of these and to the abundance of hard secondary minerals is ascribed, in a great measure, the generally high coefficient of hardness combined with good wearing qualities and low cementing value of most of these rocks.

The exceptionally high per cent of wear of chlorite and mica schists and slate is explained by the presence in these rock types of soft micaceous and chloritic minerals in large amounts, while the generally good binding power of the less metamorphic slates is due probably to hydrated silicates (kaolin, etc.) common to shale and clay, which have escaped the action of metamorphism, yet are indistinguishable microscopically from muscovite. (See p. 14.)

The structural features that have led to the separation of metamorphic rocks into foliated and nonfoliated types find expression in their behavior on the road. Thus it will be noted that rocks of the former type are less resistant to fracture, especially along their planes of schistosity, than the more massive nonfoliated varieties, and have a pronounced tendency to separate under traffic into thin plates or irregular wedge-shaped fragments, while the latter are extremely tough and break into forms having more equal dimensions.

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[a] U. S. Dept. Agr., Bureau of Chemistry, Bul. 79, p. 42.

[b] Thomas Aitken, Road Making and Maintenance, 1900, p. 94; Greenwell and Elsden, Roads: Their Construction and Maintenance, 1901, p. 62; U. S. Dept. Agr., Bu. Chem., Bul. 85, p. 14.

It might be suggested here that the factor of shape, conditioned by rock fracture generally, is very important and should not be overlooked in the selection of road material.

SUMMARY AND CONCLUSION.

In the preceding pages a microscopic method of rock analysis by means of a cross-line grating has been described, and the average mineral composition and physical properties of all rocks which have been examined in this Office have been presented in tabular form.

In view of the confusion in the terminology and classification of road materials[a] it has been considered advisable to revise the present grouping of road-making rocks and to arrange them as far as possible according to their genetic relations, as shown by their structure and mineral composition. In conformity with this plan they have been graded into classes, types, families, and subfamilies or varieties and the various distinguishing features of each group explained at length.

The mineral components of rocks have received considerable attention, both in regard to their crystallographic and physical properties as well as their chemical composition. They have been discussed under the groups of primary and secondary minerals, and their volumetric percentages in road-making rocks have been given.

To explain the bearing of mineral composition and structure on the physical properties of rocks, it has been found necessary to define these properties and describe the various methods for testing road materials. The results of these tests have been used in correlating the physical properties of the various rock families with their mineral components, and the following conclusions have been reached:

(1) Igneous and metamorphic rocks, owing to a higher degree of crystallization and a preponderance of silicate minerals, offer a greater resistance to abrasion than nearly all varieties of sedimentary rocks.

(2) The coarse-grained intrusive rocks of the igneous class are harder, but break more readily under impact than the finer-grained volcanic varieties of like mineral composition.

(3) The deleterious effect of atmospheric weathering on the wearing qualities of rocks has been demonstrated.

(4) The cementing value of rocks is, to a certain degree, measured by the abundance of secondary minerals resulting from rock decay.

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[a] Surveyor, 1907, **31**, 406.

(5) Metamorphic rocks have, as a rule, a low binding power, owing to a regeneration of secondary minerals and to the effects of heat and pressure. The foliated types part readily along planes of schistosity, and therefore are not well adapted to road construction.

(6) The quantitative mineral analysis of rocks serves to a certain extent as a measure of their useful properties for road construction.

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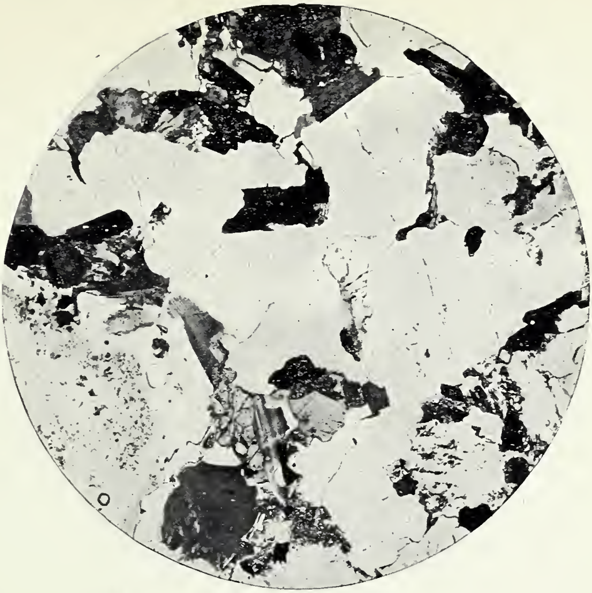

FIG. 1.—GRANITE.

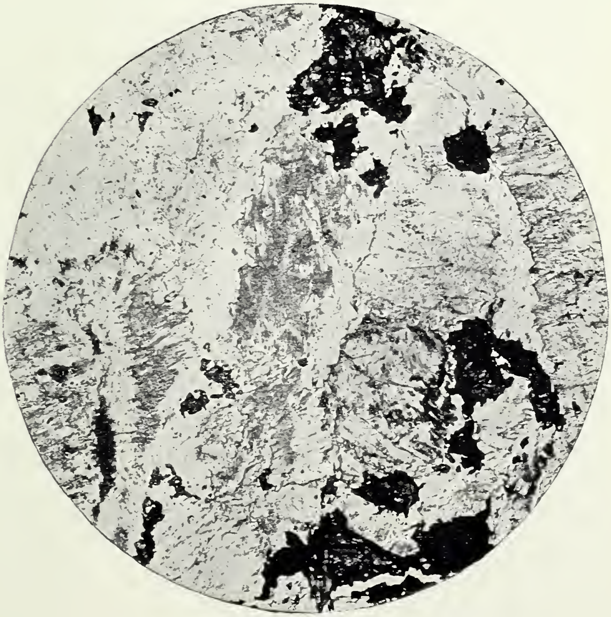

FIG. 2.—SYENITE.

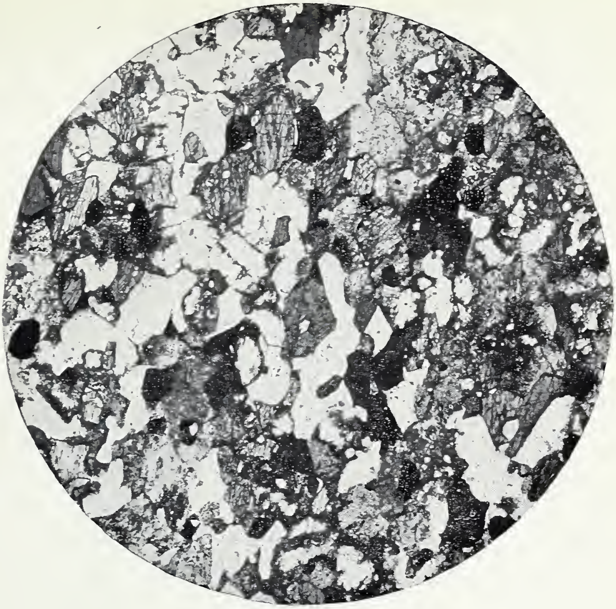

FIG. 1.—DIORITE.

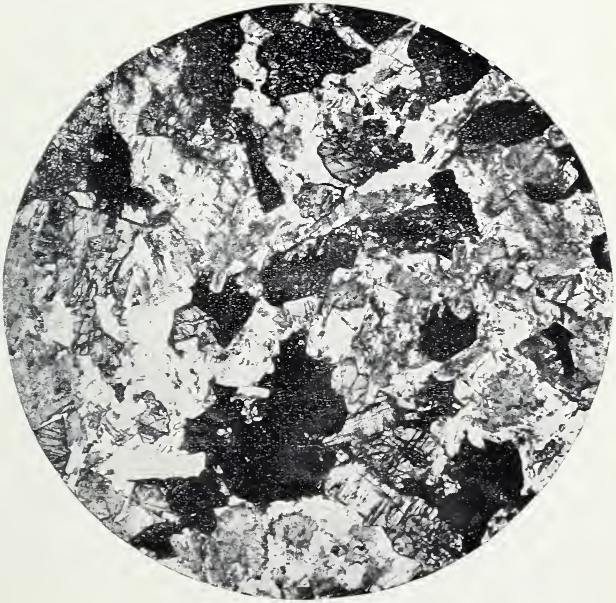

FIG. 2.—GABBRO.

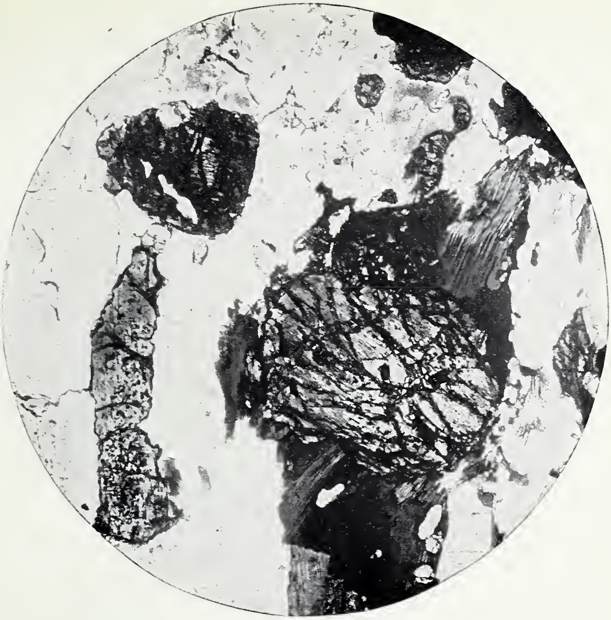

FIG. 1.—HYPERSTHENE-GABBRO.

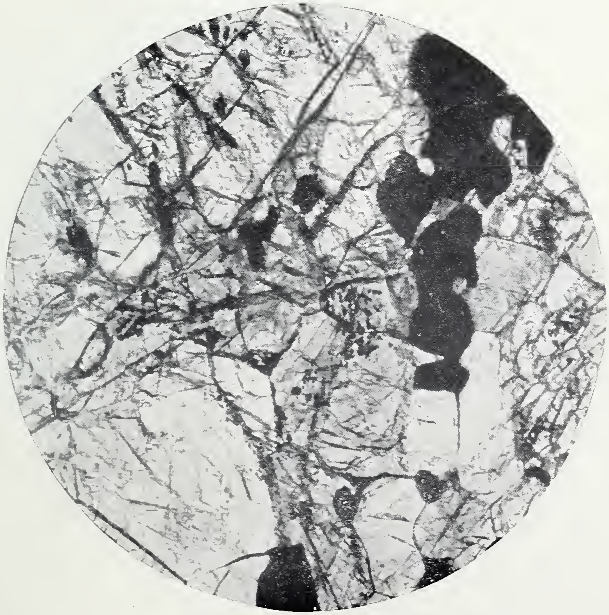

FIG. 2.—PERIDOTITE.

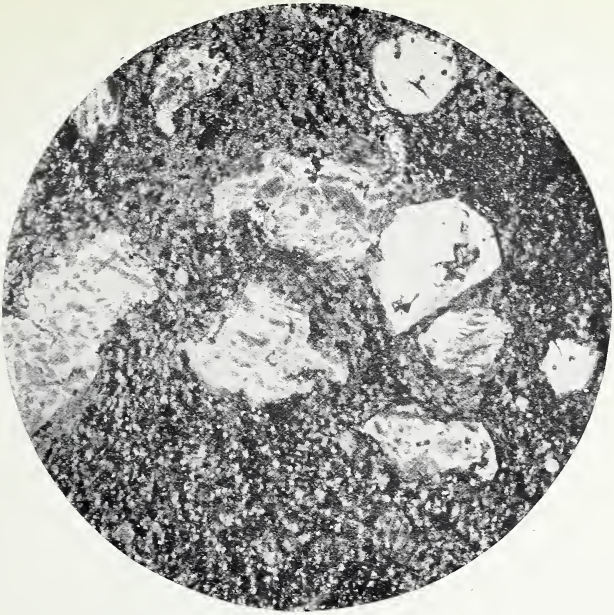

FIG. 1.—RHYOLITE.

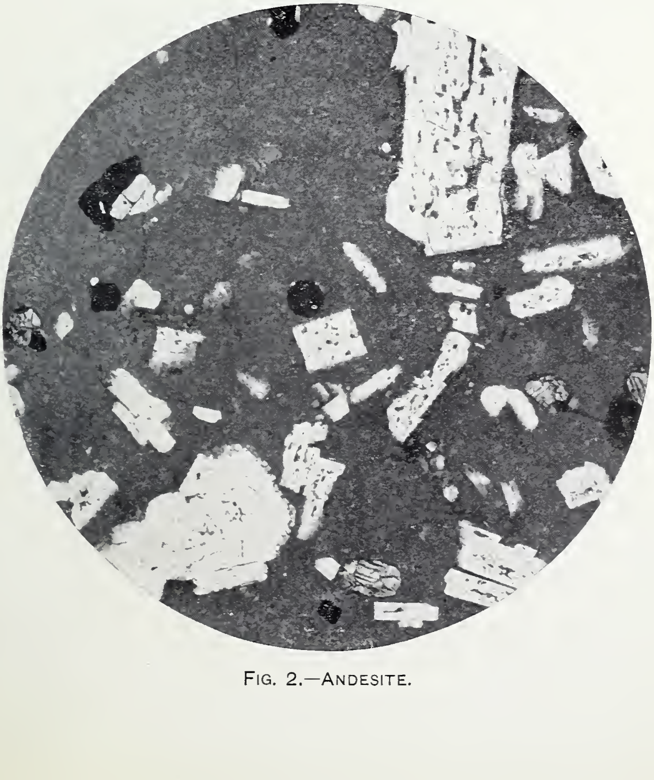

FIG. 2.—ANDESITE.

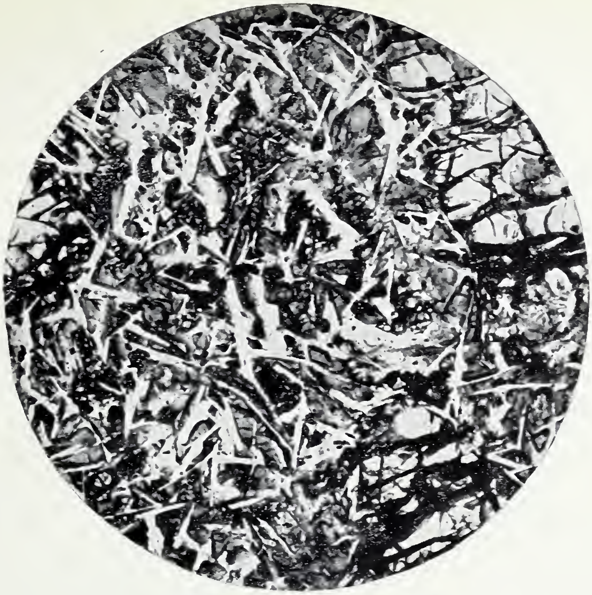

FIG. 1.—BASALT (TRAP).

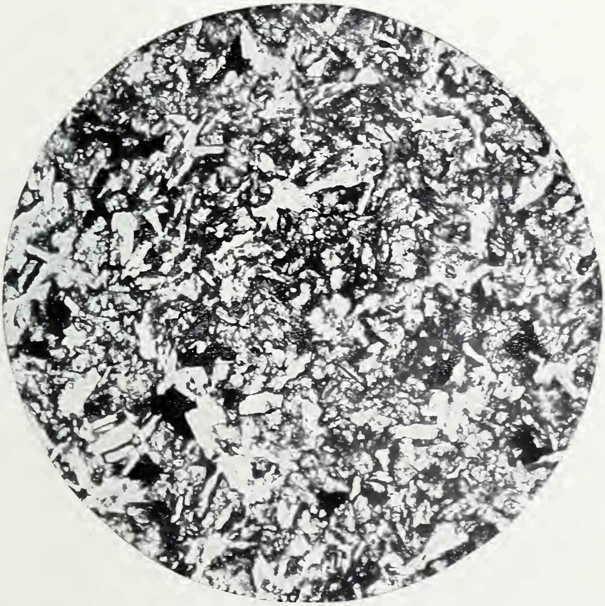

FIG. 2.—DIABASE (TRAP).

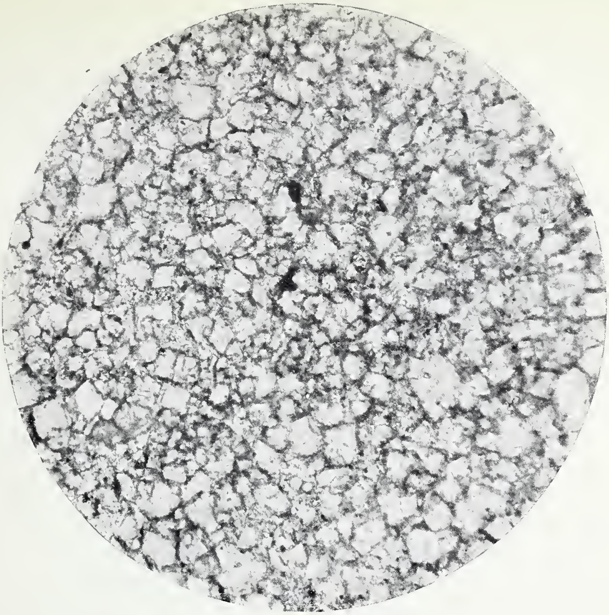

FIG. 1.—CRYSTALLINE LIMESTONE.

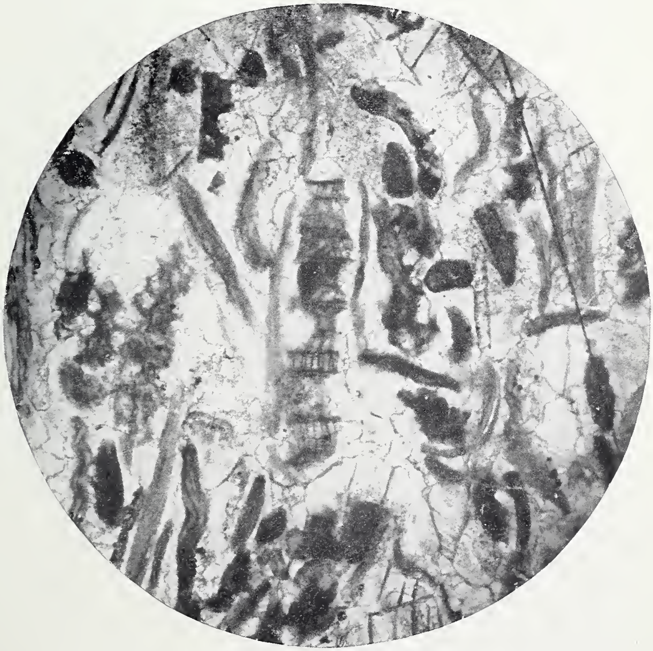

FIG. 2.—FOSSILIFEROUS LIMESTONE.

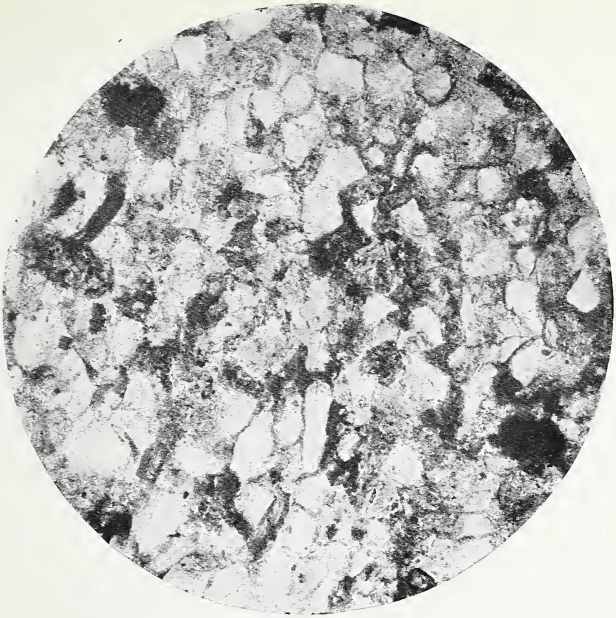

FIG. 1.—SANDSTONE.

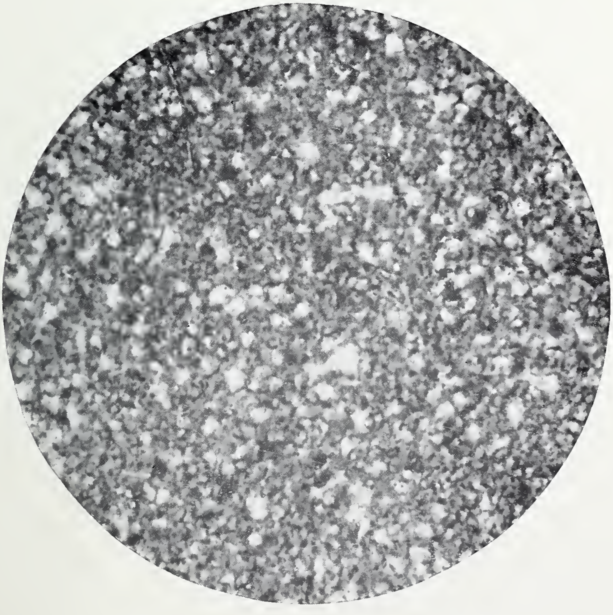

FIG. 2.—CHERT.

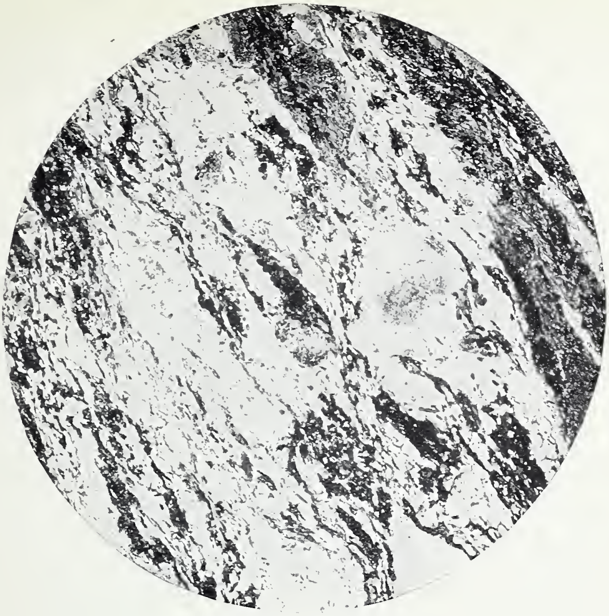

FIG. 1.—GRANITE-GNEISS.

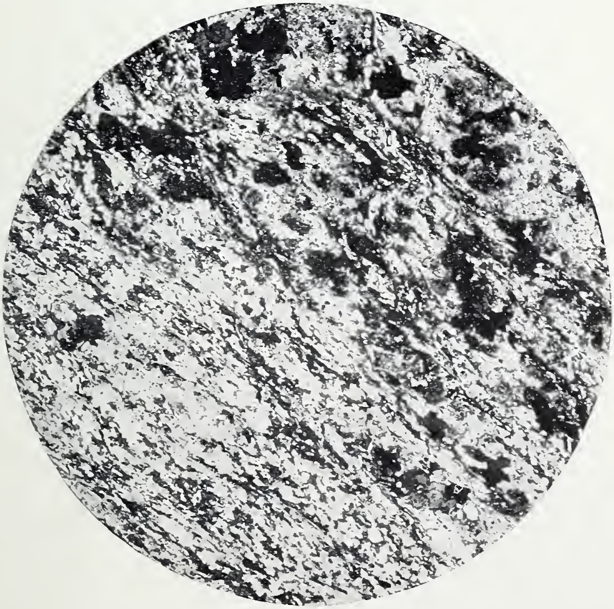

FIG. 2.—MICA-SCHIST.

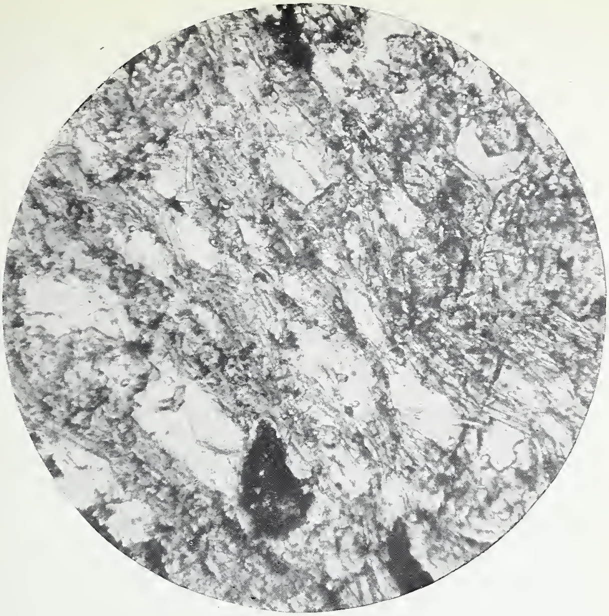

FIG. 1.—CHLORITE-SCHIST.

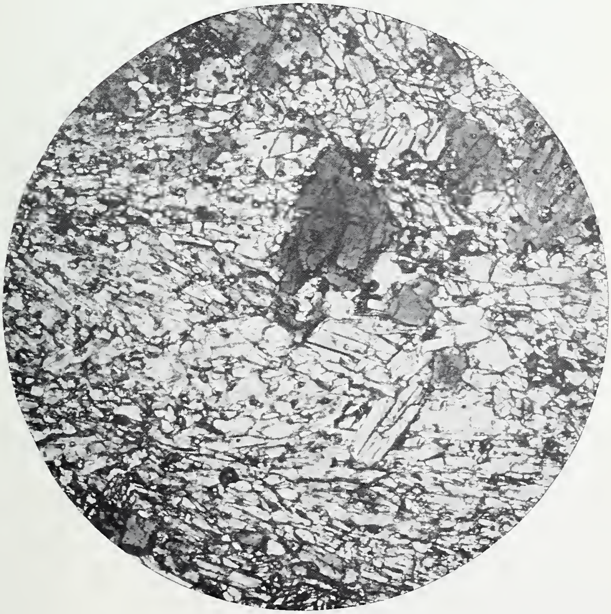

FIG. 2.—AMPHIBOLITE.

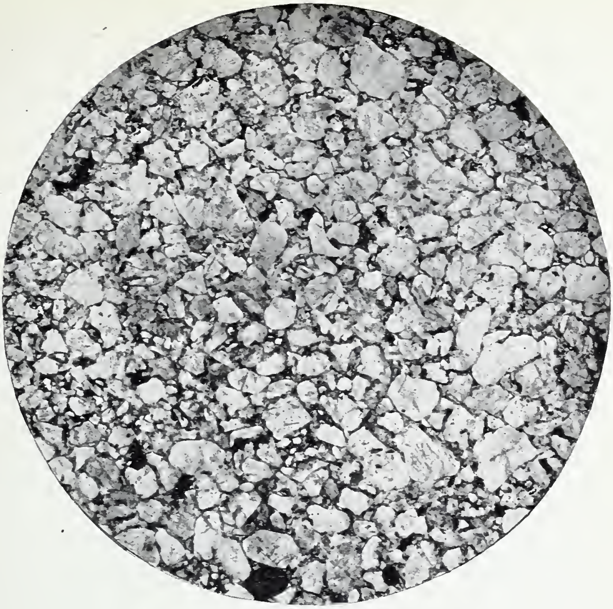

FIG. 1.—QUARTZITE.

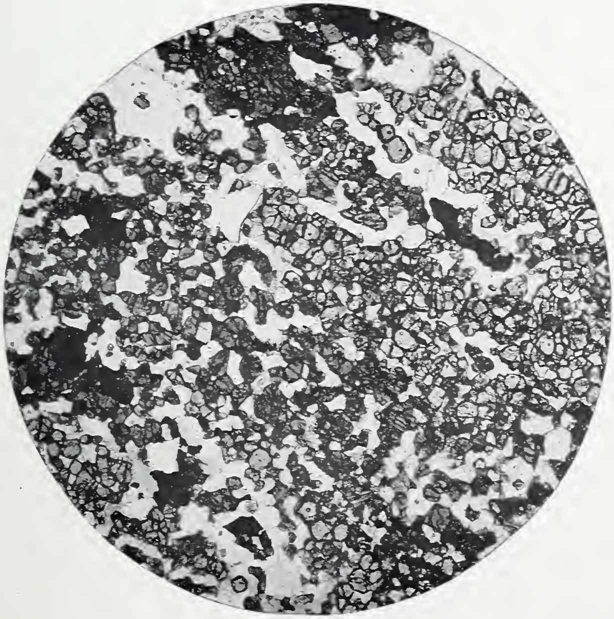

FIG. 2.—ECLOGITE.